

THE BESS MODEL AT FUTURE COLLIDERS*

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ABSTRACT

The BESS model consists of an effective lagrangian parametrization with dynamical symmetry breaking, describing scalar, vector and axial-vector bound states in a rather general framework. After a brief description of the model and its generalizations, predictions for physics at future accelerators are given both for LHC and e^+e^- machines.

1. Introduction

The mechanism for symmetry breaking in the standard model is usually regarded as unsatisfactory. More fundamental realizations lead to the expectation that higher energy accelerators might reveal new particles and interactions. Our parametrization in terms of scalar couplings may in fact represent the effective low energy manifestation of more fundamental dynamics, with additional particles and interactions.

The fundamental dynamics may have the form of a new strong interaction ^{1 2}, but the construction of a satisfactory technicolor theory is a difficult task and in the absence of a specific theory of the strong electroweak sector, one would like to remain as general as possible, avoiding specific dynamical assumptions. The BESS model ³ (Breaking Electroweak Symmetry Strongly) was essentially developed to provide for such a general frame (for a review see ⁴).

2. BESS

In the standard model (SM) the symmetry breaking is realized linearly with scalars originally transforming as the $(\frac{1}{2}, \frac{1}{2})$ of $SU(2)_L \otimes SU(2)_R$. The direct product breaks into $SU(2)_{diagonal}$, with corresponding breaking of $(\frac{1}{2}, \frac{1}{2})$ into $1 \oplus 3$, describing the physical Higgs and the 3 absorbed Goldstones.

The non-linear realization of symmetry breaking I shall consider in the following, can be seen classically to correspond to the limit of infinite m_H . The scalars can be represented as proportional to a unitary matrix U . In the formal limit $m_H \rightarrow \infty$ one is freezing the proportionality factor to the vacuum expectation value and the scalar lagrangian is the lagrangian of a non linear σ -model described by a unitary matrix U , invariant under $SU(2)_L \otimes SU(2)_R$, namely under $U \rightarrow g_L U g_R^\dagger$ where g_L, g_R belong to $SU(2)_L, SU(2)_R$ respectively. The breaking into the diagonal $SU(2)$ is demanded by the non-linear unitarity condition $U^\dagger U = 1$.

The idea is to construct a model with vector and axial-vector particles, so that when these particles decouple one obtains the non linear σ -model lagrangian. Indeed, one may consider a more general case and start from a global symmetry $SU(N)_L \otimes SU(N)_R$ ⁵, rather than $SU(2)_L \otimes SU(2)_R$ ³. In order to do that, one introduces a local copy of the global symmetry, $[SU(N)_L \otimes SU(N)_R]_{local}$. When the new vector and axial-vector particles decouple, one obtains the non-linear σ -model lagrangian, describing the Goldstone bosons, transforming as the representation (N, N) of $SU(N)_L \otimes SU(N)_R$, associated to the breaking of $SU(N)_L \otimes SU(N)_R \rightarrow SU(N)_{L+R}$

$$\mathcal{L} = \frac{v^2}{2N} \text{Tr} [(\partial_\mu U)(\partial^\mu U)^\dagger] \quad (1)$$

To introduce both vector and axial-vector particles, I assume the following factorization of U

$$U = LM^\dagger R^\dagger \quad (2)$$

where L , M , R , transform according to the representations of

$$G = [SU(N)_L \otimes SU(N)_R]_{global} \otimes [SU(N)_L \otimes SU(N)_R]_{local} \quad (3)$$

as

$$L \in (N, 0, N, 0) \quad M \in (0, 0, N, N) \quad R \in (0, N, 0, N) \quad (4)$$

which means

$$L' = g_L L h_L \quad M' = h_R^\dagger M h_L \quad R' = g_R R h_R \quad (5)$$

where

$$\begin{aligned} g_L &\in (SU(N)_L)_{global} & g_R &\in (SU(N)_R)_{global} \\ h_L &\in (SU(N)_L)_{local} & h_R &\in (SU(N)_R)_{local} \end{aligned} \quad (6)$$

In this way U does not transform under the local symmetry (hidden gauge symmetry⁶):

$$U' = g_L U g_R^\dagger \quad (7)$$

that is,

$$U \in (N, N, 0, 0) \quad (8)$$

The Lagrangian in Eq.(1) is invariant under the discrete transformation $U \rightarrow U^\dagger$, which corresponds to (parity transformation):

$$L \rightarrow R \quad M \rightarrow M^\dagger \quad R \rightarrow L \quad (9)$$

Covariant derivatives can be built with respect to the local group:

$$\begin{aligned} D_\mu L &= \partial_\mu L - L \mathbf{L}_\mu \\ D_\mu R &= \partial_\mu R - R \mathbf{R}_\mu \\ D_\mu M &= \partial_\mu M - M \mathbf{L}_\mu + \mathbf{R}_\mu M \end{aligned} \quad (10)$$

where \mathbf{L}_μ and \mathbf{R}_μ are the Lie algebra valued gauge fields of $(SU(N)_L)_{local}$ and $(SU(N)_R)_{local}$ respectively.

The invariants of our original group extended by the parity operation defined in Eq.(9) are:

$$I_1 = \text{Tr}(L^\dagger D_\mu L - M^\dagger D_\mu M - M^\dagger R^\dagger (D_\mu R) M)^2 \quad (11)$$

$$I_2 = \text{Tr}(L^\dagger D_\mu L + M^\dagger R^\dagger (D_\mu R) M)^2 \quad (12)$$

$$I_3 = \text{Tr}(L^\dagger D_\mu L - M^\dagger R^\dagger (D_\mu R) M)^2 \quad (13)$$

$$I_4 = \text{Tr}(M^\dagger D_\mu M)^2 \quad (14)$$

Using these invariants I can write the most general Lagrangian with at most two derivatives in the form:

$$\mathcal{L} = -\frac{v^2}{2N}(aI_1 + bI_2 + cI_3 + dI_4) + \text{kinetic terms for the gauge fields} \quad (15)$$

where a, b, c, d are free parameters and furthermore the gauge coupling constant for the fields \mathbf{L}_μ and \mathbf{R}_μ is the same.

The requirement of getting back to the non-linear σ -model in the limit in which the gauge fields \mathbf{L}_μ and \mathbf{R}_μ are decoupled is satisfied by imposing the relation $a + zd = 1$ where

$$z = \frac{c}{c + d} \quad (16)$$

The case $z = 0$ corresponds to the decoupling of the axial-vector resonances.

Gauging the previous effective Lagrangian with respect to the standard gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_R$:

$$D_\mu L \rightarrow D_\mu L = \partial_\mu L - L(V_\mu - A_\mu) + \mathbf{A}_\mu L \quad (17)$$

$$D_\mu R \rightarrow D_\mu R = \partial_\mu R - R(V_\mu + A_\mu) + \mathbf{B}_\mu R \quad (18)$$

$$D_\mu M \rightarrow D_\mu M = \partial_\mu M - M(V_\mu - A_\mu) + (V_\mu + A_\mu)M \quad (19)$$

where $V_\mu = (\mathbf{R}_\mu + \mathbf{L}_\mu)/2$ and $A_\mu = (\mathbf{R}_\mu - \mathbf{L}_\mu)/2$ are the fields describing the new vector and axial-vector resonances, whereas \mathbf{A}_μ and \mathbf{B}_μ are linear combinations of the gauge fields of the standard gauge group.

In the following I shall consider the two cases $N = 2$ and $N = 8$, to which the quantitative discussion will be limited, except for some occasional more general remark. The $SU(2)$ case has 3 new vector and 3 new axial-vector resonances. The $SU(8)$ case is obviously much richer and can be specialized to standard $SU(8)$ technicolor; in this case also spin-0 pseudo-Goldstone particles are present in the spectrum.

I shall denote the $SU(8)$ gauge fields as $V^A = (V^a, \tilde{V}^a, V_D, V_8^\alpha, V_8^{a\alpha}, V_3^{\mu i}, \bar{V}_3^{\mu i})$, where $\mu = (0, a)$ (a being an $SU(2)$ index), α an octet index and $i = 1, 2, 3$ is a color index. An analogous notation will be used for A^A and the Goldstone bosons π^A . In the following I shall use the notations:

$$\mathbf{A}_\mu = 2igW_\mu^a T^a + i\sqrt{2}g_s G_\mu^\alpha T_8^\alpha + 2iyg' Y_\mu T_D \quad (20)$$

$$\mathbf{B}_\mu = 2ig'Y_\mu(T^3 + yT_D) + i\sqrt{2}g_sG_\mu^\alpha T_8^\alpha \quad (21)$$

$$V_\mu = ig''V_\mu^A T^A \quad (22)$$

$$A_\mu = ig''A_\mu^A T^A \quad (23)$$

with $A, B = 1, \dots, 63$; $a, b = 1, 2, 3$; $\alpha, \beta = 1, \dots, 8$ and $y = 1/\sqrt{3}$; W, Y, G are the standard model gauge bosons and g, g', g_s their coupling constants, while g'' is the self coupling of the V and A bosons. The V and A bosons can be decoupled by sending $g'' \rightarrow \infty$. In this limit, the mass of the W bosons is the SM mass with $v \simeq 246 \text{ GeV}$.

3. e^+e^- future colliders

Future e^+e^- linear colliders with different centre of mass energies and luminosities have been proposed; a collider with energy up to 500 GeV has concentrated most of the studies ⁷, but at the same time possibilities of centre of mass energies of 1 or 2 TeV have been discussed ⁸.

The BESS model, even in its minimal formulation, contains new vector resonances. If the mass M_V of the new boson multiplet lies not far from the maximum machine energy, or if it is lower, such a resonant contribution will be manifest.

One can measure the fermionic channel $e^+e^- \rightarrow f\bar{f}$, but this will not give a real improvement with respect to the existing bounds from LEP1. In Fig. 1 restrictions on the parameter space of the model from LEP1 data are obtained in the low energy limit of the BESS model. The method consists in eliminating the heavy vector field by the use of its classical equations of motion, in the infinite mass limit. After the elimination of the heavy degrees of freedom the additional terms to the Standard Model lagrangian allow to read directly the deviations from the Standard Model ⁹. On the other hand, the process of W -pair production by e^+e^- annihilation would allow for sensitive tests of the strong sector ¹⁰, especially if the W polarizations are reconstructed from their decay distributions. The importance of this decay channel is due to the strong coupling between the longitudinal W bosons and the new neutral resonance V^0 ; furthermore in BESS the Standard Model cancellation among the γ - Z exchange diagrams and the neutrino contribution is destroyed. Therefore the differential cross section grows with the energy. Explicit calculations show that the leading term in s is however suppressed by a factor $(g/g'')^4$ and, at the energies considered here, it is the constant term of the order $(g/g'')^2$ that matters.

Final W polarization reconstruction can be done considering one W decaying leptonically and the other hadronically and it is relevant to constrain the model, even if already at the level of unpolarized cross section one gets important restrictions. Assuming an integrated luminosity of 20 fb^{-1} , $\sqrt{s} = 500 \text{ GeV}$ and $b = 0$, it is possible to improve the LEP1 limit on g/g'' over the whole M_V range if polarization is measured, up to $M_V \approx 1 \text{ TeV}$ for unpolarized W .

W^+W^- pairs can be produced also through a mechanism of fusion of a pair of ordinary gauge bosons, each being initially emitted from an electron or a positron.

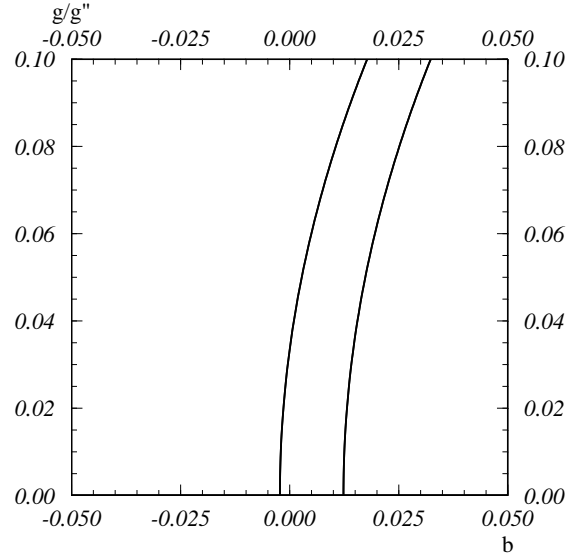


Fig. 1. 90% C.L. contour in the plane $(b, g/g'')$ in the limit of large M_V , from LEP data (Glasgow Conference 1994), SLD and low energy data, with $m_{top} = 174$ GeV, $\alpha_s = 0.120$, and $\Lambda = 1$ TeV. The limits on the parameter space are obtained eliminating the heavy vector field by the use of its classical equations of motion, in the infinite mass limit. After the elimination of the heavy degrees of freedom the additional terms to the Standard Model lagrangian allow to read directly the deviations.

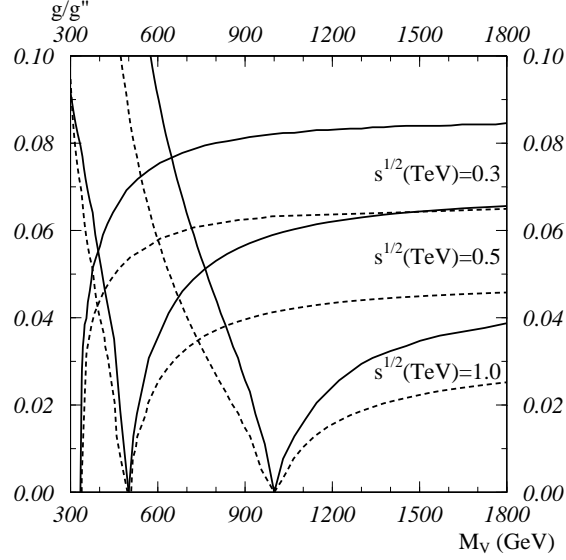


Fig. 2. 90% C.L. contours in the plane $(M_V, g/g'')$ for $\sqrt{s} = 0.3, 0.5, 1 \text{ TeV}$, $L = 20 \text{ fb}^{-1}$ and $b = 0$. The solid line corresponds to the bound from the unpolarized WW differential cross section, the dashed line to the bound from all the polarized differential cross sections $W_L W_L$, $W_T W_L$, $W_T W_T$ combined with the WW left-right asymmetries. The lines give the upper bounds on g/g'' .

This process allows, for a given centre of mass energy, to study a wide range of mass spectrum for the V resonance, but it becomes important only for energies bigger than 2 TeV.

In Fig. 2 the restrictions in the plane $(M_V, g/g'')$ are given (with $b = 0$) for three different choices of the collider energy, assuming an integrated luminosity of 20 fb^{-1} .

In Fig. 3 the upper bounds on g/g'' for $M_V = 1.5 \text{ TeV}$ and $b = 0$ are shown as a function of the center of mass energy of the e^+e^- collider in the case no deviation from the SM is found. The relevance of final W polarization reconstruction over the unpolarized cross section (solid line) is apparent in the whole energy range considered. A higher luminosity option is shown for the case $\sqrt{s} = 1 \text{ TeV}$ and $L = 80 \text{ fb}^{-1}$ (black dots).

In conclusion e^+e^- colliders could give the possibility to study the neutral sector of symmetry breaking; $V^0 - Z$ mixing, $V^0 f \bar{f}$ and $V^0 W^+ W^-$ couplings. This is complementarity to pp colliders (LHC), allowing to explore V^\pm resonances through the decay channel $W^\pm Z$. At proton colliders, the channel $V^0 \rightarrow W^+ W^-$ is difficult

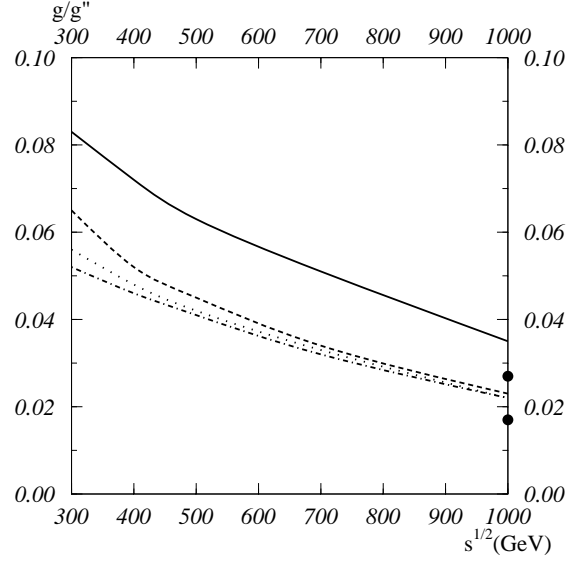


Fig. 3. 90% C.L. contours in the plane $(\sqrt{s}, g/g'')$ for $M_V = 1.5 \text{ TeV}$, $b = 0$ and $L = 20 \text{ fb}^{-1}$. The lines correspond to the unpolarized WW differential cross section (solid line), the $W_L W_L$ differential cross section (dashed line), and all the differential cross sections for $W_L W_L$, $W_T W_L$, $W_T W_T$ combined with the WW left-right asymmetries (dotted line) and from all the WW and fermionic observables with $P_e = 0.5$ (dash-dotted line) and represent the upper bounds on g/g'' . The black dots are the bounds for the unpolarized WW differential cross section and from all the WW and fermionic observables at $\sqrt{s} = 1 \text{ TeV}$ and $L = 80 \text{ fb}^{-1}$.

to study due to background problems, and $V^0 \rightarrow l^+l^-$ has a very low rate.

Linear e^+e^- colliders give also the possibility to study the production of pairs of charged pseudo-Goldstone bosons, which are present in the extended version of the model¹¹. They can be produced at the V resonance through the process $e^+e^- \rightarrow V \rightarrow P^+P^-$, where P^\pm are the lightest charged pseudo-Goldstone bosons. The problem of the evaluation of their masses was investigated in¹²; the idea is to consider effective Yukawa couplings between ordinary fermions and pseudos. The pseudo-Goldstone mass spectrum can be derived from the one-loop effective potential. The resulting masses are expected to lie in a range depending on the masses of the heaviest fermions.

The main decay mode of a charged P is $P^+ \rightarrow t\bar{b}$, if the pseudo-Goldstone is heavy enough. It is therefore necessary to analyze the final state $P^+P^- \rightarrow t\bar{b}t\bar{b}$, and compare it with the background. There are three background sources: $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow ZZ$, $e^+e^- \rightarrow t\bar{t}$. Tagging one b in the final state easily reduces the background $e^+e^- \rightarrow W^+W^-$, while the other two sources are smaller than the signal, at least in a reasonable range of the model parameter space.

4. BESS at LHC

The physics of large hadron colliders has been extensively discussed in a number of papers (see for example¹³ and references therein); for what concerns BESS I shall examine two possible mechanisms to produce V resonances; $q\bar{q}$ annihilation and $WW(WZ, ZZ)$ fusion. In the first mechanism a quark-antiquark pair annihilates into a V , which decays mostly into a pair of ordinary gauge bosons because the couplings $V^0W_L^+W_L^-$ and $V^\pm W_L^\mp Z_L$ are strong (in BESS there is no coupling V^0ZZ). This process of annihilation always takes place in BESS, even if $b = 0$, due to the mixing between ordinary and new gauge bosons.

The second mechanism goes through fusion of a pair of ordinary gauge bosons, both of them initially emitted from a quark or antiquark leg, to give a V resonance decaying into a pair $W^\pm Z$ or W^+W^- . The cross section is obtained by a double convolution of the fusion cross section with the luminosities of the initial W/Z 's inside the quarks and the structure function of the quarks inside the protons. In the $q\bar{q}$ annihilation only the convolution with the structure functions of the quarks is needed. The amplitude of the elementary fusion process is strong in BESS: in fact the scattering of two longitudinally polarized W/Z 's proceeds via the exchange of a V vector boson with large couplings (of the order g'' at each vertex). As I pointed out before, the interesting channel at proton colliders is $pp \rightarrow W^\pm Z + X$, because the W^+W^- channel has a strong background from $pp \rightarrow t\bar{t} + X$ and the ZZ one is not resonant in BESS.

So far I have discussed the effects of the triplet of vector resonances V . The real situation could be more complex: axial-vector resonances might modify in a relevant way the predictions of the minimal model with only vectors¹⁴. As a general feature, virtual effects and deviations from the Standard Model coming from the vector and axial-vector sector tend to cancel each other, and the final effects depend

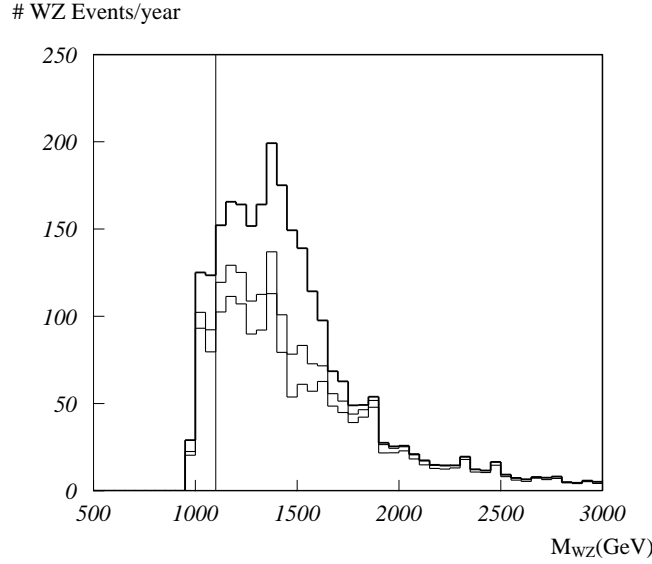


Fig. 4. Invariant mass distribution of the W^+Z+W^-Z pairs produced per year at LHC ($\sqrt{s} = 16$ TeV) for $M_V = 1500$ GeV, $g'' = 13$ and $z = 0$ within BESS $SU(8) \otimes SU(8)$, with a luminosity of 100 fb^{-1} . The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_Z > 480$ GeV and $M_{WZ} > 1100$ GeV. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

on the relative weight of the two contributions. In some region of the parameter space of the model there could be complete cancellations and no deviations from the Standard Model would be observed, at least at energies below the new resonances. The discovery of a strong electroweak sector only through virtual effects and precision measurements could therefore be difficult. The direct discovery of new resonances at the TeV scale would be in such a case determinant. This is experimentally easy if the width of the resonance is not too broad (the width increases with the mass M_V and decreases with g''), while for higher masses (or smaller g'') the discovery potential is reduced; in particular the shape of the jacobian peak does not differ from the background, the signal leading only to an excess of events.

In the extended BESS model a richer phenomenology appears. There are $N^2 - 1$ vector and $N^2 - 1$ axial-vector new resonances, associated to the local copy of the global $SU(N)_L \otimes SU(N)_R$. These resonances mix with the ordinary gauge bosons: in the case $N = 8$ the neutral gauge sector involves the mixing of the fields W^3, Y, V^3, A^3, V_D . V_D is a chiral singlet, and its mixing makes the colorless gauge

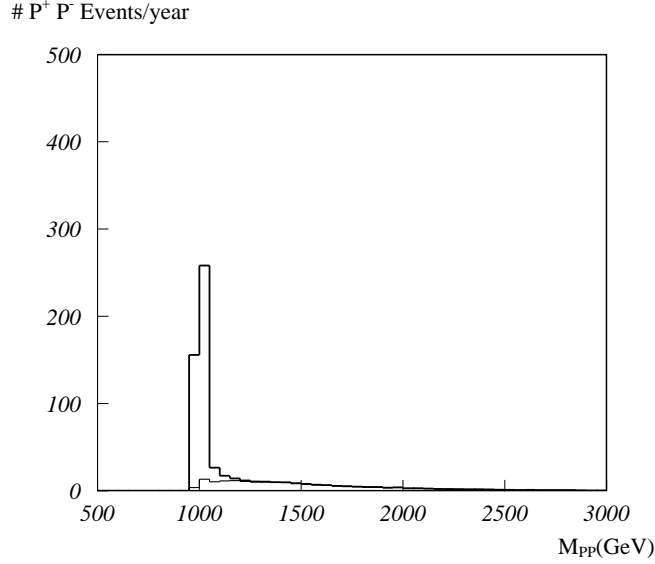


Fig. 5. Invariant mass distribution of the P^+P^- produced per year at LHC for $M_P \simeq 400$ GeV, $M_V = 1000$ GeV, $g'' = 13$ and $z = 0$, with a luminosity of 100 fb^{-1} . The applied cuts are: $|y_P| < 2.5$, $(p_T)_{P^0} > 300$ GeV. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

sector of $SU(8)$ -BESS different from the model based on $SU(2)_L \otimes SU(2)_R$. The W^\pm , V^\pm and A^\pm sector is like in $SU(2)$ -BESS. Concerning the colored sector, the $SU(3)_c$ gluons mix with a color octet of vector resonances V_8^α

Another new feature is the presence of pseudo-Goldstone bosons. For quantitative estimates of the pseudo-Goldstone production cross-sections, I shall employ the $SU(8) \otimes SU(8)$ extended BESS model. Earlier studies on PGB phenomenology in technicolor theories^{15 16} can be found in the bibliography and references therein. The production is induced by the processes¹¹

$$f^+ + f^- \rightarrow \gamma, Z, V^3 \rightarrow P^+ P^- \quad (24)$$

and

$$f_1 + f_2 \rightarrow W^\pm, V^\pm \rightarrow P^\pm P^0 \quad (25)$$

where $P^\pm(P^0)$ denote the lightest charged (neutral) PGB's and f denotes a light fermion.

5. Conclusion

The process of W -pair production by e^+e^- annihilation will allow for a sensitive tests of the strong interacting sector, especially if the W polarizations will be reconstructed from their decay distributions. The importance of this decay channel is due to the strong coupling between the longitudinal W bosons and the neutral resonance V^0 .

The LHC will be able to test the presence of a charged vector resonance from a strong interacting Higgs sector through its decay into WZ pairs in a significant domain of the extended BESS model parameter space.

Production of pairs of pseudo-Goldstone bosons $P^\pm P^0$ is also important, but discovery via $tbbb$ or $ttgg$ decays needs a careful evaluation of backgrounds in the LHC environment.

A more promising possibility is the production of charged pseudo-Goldstones at the V resonance in e^+e^- collisions in the TeV range. In fact the largest background, namely WW production, can be easily reduced to a very low level by requiring the tagging of one b in the final state. Other backgrounds, such as ZZ and $t\bar{t}$ production, have smaller cross-sections as compared with signal cross-section, at least in a range of the parameter space of the model. For increasing values of the M_V mass and decreasing values of the z parameter the signal cross-section becomes smaller than background and deserves a detailed study of background rejection.

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